International Journal of Electrical and
Electronics Engineering Research (IJEEER)
ISSN(P): 2250-155X; ISSN(E): 2278-943X
Vol. 4, Issue 3, Jun 2014, 85-94

PERFORMANCE ANALYSIS OF PHOTONIC CRYSTAL 1x4 POWER SPLITTERS FOR OPTICAL NETWORK

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ABSTRACT

A novel design of 1x4 fixed and flexible power splitters on 2D Photonic crystal (PC) is proposed. Two types of PC's were used in our work.1) PC with airholes in dielectric background 2) PC with dielectric rods in air. When PC was integrated with planar Multi mode interference coupler (MMI), compact and flexible Power splitters could be realized. FDTD method was used for the investigation. Coupled mode theory (CMT) was used to understand the super mode patterns and coupling characteristics. The device size reduction compared with the conventional MMI power splitter would be attributed to the large dispersion of the PC. Two devices were simulated at 1550nm and their performances were compared on the basis of coupling power and device length.

KEYWORDS: Power Splitter, PC, MMI Coupler, FDTD, CMT and Dispersion

1. INTRODUCTION

Power splitting is the basic function of the integrated optics. Such devices play a vital role in passive optical distribution network, complex photonic integrated circuits as well as advanced active components such as interferometer, switches (Bachmann et al 1994), (Besse et al 1995) and nonlinear all optical devices. In the last few decades various solutions have proposed to split and combine optical signal.MMI coupler based power splitters are popular due their compact structure, polarization insensitivity and tolerance to fabrication parameter (Besse et al 1996). By using conventional rectangular geometry of MMI coupler only discrete power splitting ratio can be obtained even when the overlapping of the self images is introduced (Soldano et al 1992). When "tap" function is required a small portion of the power is extracted. For several applications free choice of power splitting is advantages, (Besse et al1996). Ring lasers with 2x2 MMI couplers at its o/p were proposed to obtain a flexible power splitting ratio (Van et al 1994). The device is complex. Later a concept of tapering in MMI coupler was investigated (Wei et al 2001). In [9] MMI coupler with tunable power splitting ratio is realized (Leuthold & Joyner 2001). Such devices have wide tuning range, compact structure and find applications in optical switches. These devices offer around 20% tunability. Recent advances in MMI design includes polarization insensitive MMI coupler (Chiang 2011), Power splitters with variable power splitting ratio (Yang, 2011), Photonic Crystal Fiber(PCF) based power splitters (Varshney, 2009)and Adaptive power splitters (Mustafa et al 2013) are the recent technology in the field of Photonics and Fiber Optics.

The trend of miniaturizing the optical integrated devices has been boosted by the concept of photonic band gap (PBG) material discovered by Yabolonvitch in 1987 (Yablonvitch, 1987). The motivation for the discovery of PBG material is Opal which is a natural photonic Crystal. The source materials with PBG are Si, GaAS and InP. Photonic

Crystals (PC) are artificially created crystals. They have periodic systems of high and low dielectric regions. There are two types of PCs.1) Airholes in dielectric background 2) Dielectric rods in air as shown in Figure 1a & 1b. Former has a Tranverse Electric (TE) PBG and latter has Transverse Magnetic (TM) PBG as shown in Figure 2a & 2b. By introducing point and line defect in these material, cavities and waveguides with novel properties are created. Removal of airhole/rods, increase/decrease in the diameter of the air holes/rods are termed as point defect. Removal of row of airholes/rods is known as line defect as depicted in Figure 3.

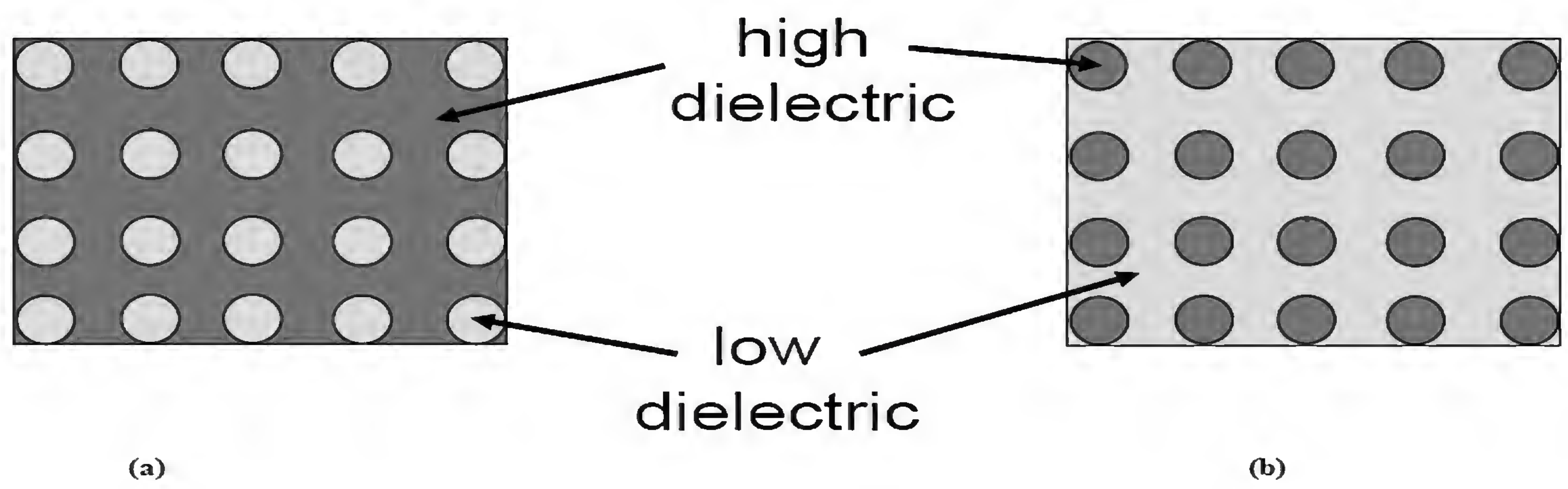


Figure 1: a) PC with Periodic Airholes in Dielectric Background
b) PC with Dieleciric Cylinders in Air

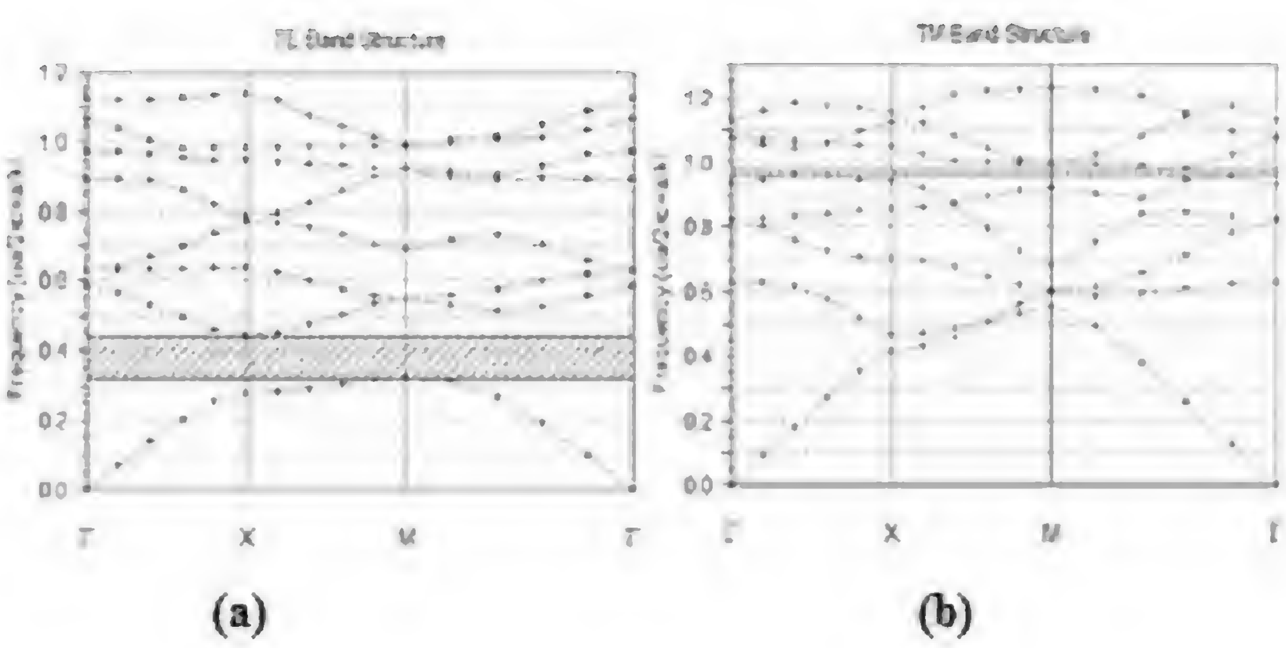


Figure 2: a) TE Band Structure for PC with Air Holes in Dielectric Background
b) TM Band Structure for PC with Rods in Air

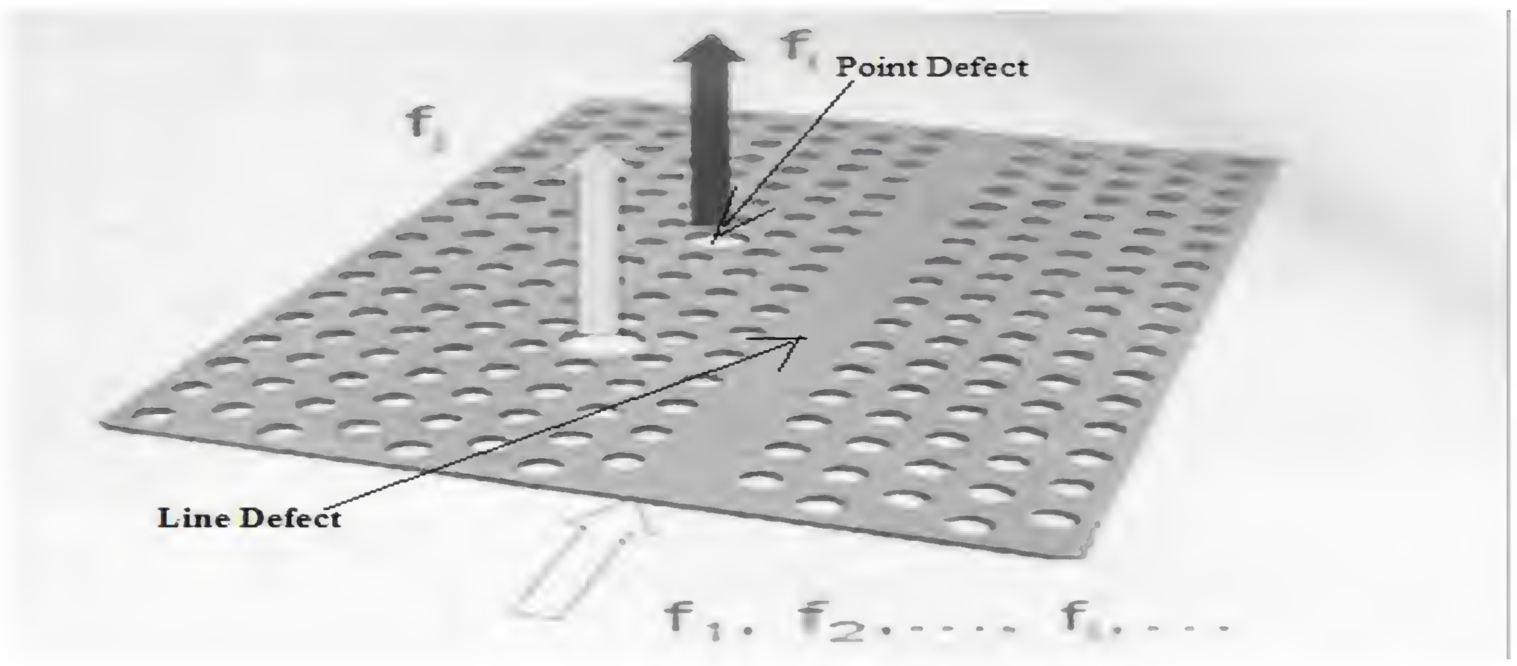


Figure 3: PC with Point and Line Defect

Several designs addressing the power splitting phenomenon have been suggested. However they have some draw backs such as propagation losses, lack of dual functionality, design problems in bending and coupling loss. Considering these factors We decided to create a novel design of Power splitter on 2D Photonic crystal. This device is multifunctional and has several applications when only a part of the optical power is required for a specific purpose.

This paper is divided into four major sections. Section 2 describes theory of 1x4Power Splitter. Section 3 describes the simulation results. Finally section four provides some conclusions.

2. THEORY

In this paper, we have integrated MMI coupler and PCW array to design and analyze 1x4 Power Splitter with flexible power splitting ratio and fixed ratio. The light enters the MMI coupler and diverges, finally enters the four o/p waveguides. The amount of power coupled to the o/p waveguides depends on the width and effective index of the waveguide. The power coupled to the o/p waveguide is controlled by varying the d/a ratio of the dielectric rods. Where "d" is the diameter of the rod/air holes and parameter "a" represents the periodicity of the lattice. Further the amount of power coupled from the MMI coupler o the o/p waveguides depends on the divergence angle of the beam in the MMI region.

2.1 Design of 1x4 Power Splitter on PC with Dielectric Rods in Air

The proposed 1x4 power splitter is schematically depicted in Figure 4. The width of the i/p waveguide (b)=1µm which is a single mode waveguide.MMI coupler is a slab waveguide with refractive index n=3.45.The dimension of the MMI coupler is 5x10µm.MMI coupler is integrated with PCW array.PCW array is a square lattice of dielectric rods in air. The radius, and the refractive index of the rods are taken r=0.2a and n=3.45.Where "a" is the lattice constant and "n" is the refractive index. The four Photonic Crystal (PC) waveguides are created by eliminating four rows of rods. (Creating line defect in PC) and the diameter of the rods adjacent to the waveguides are varied as a/λ,a/2λ and a/3λ where λ is the operating wavelength(creating point defect in PC). When fixed power splitting is required, all the o/p waveguides are of equal width. Here creating a point defect is not desirable. The thickness of the guiding layer is 150nm.Substrate thickness is 500nm. These o/p PC waveguides are replacing the conventional waveguides. The refractive index profile of the proposed device is depicted in Figure 5.

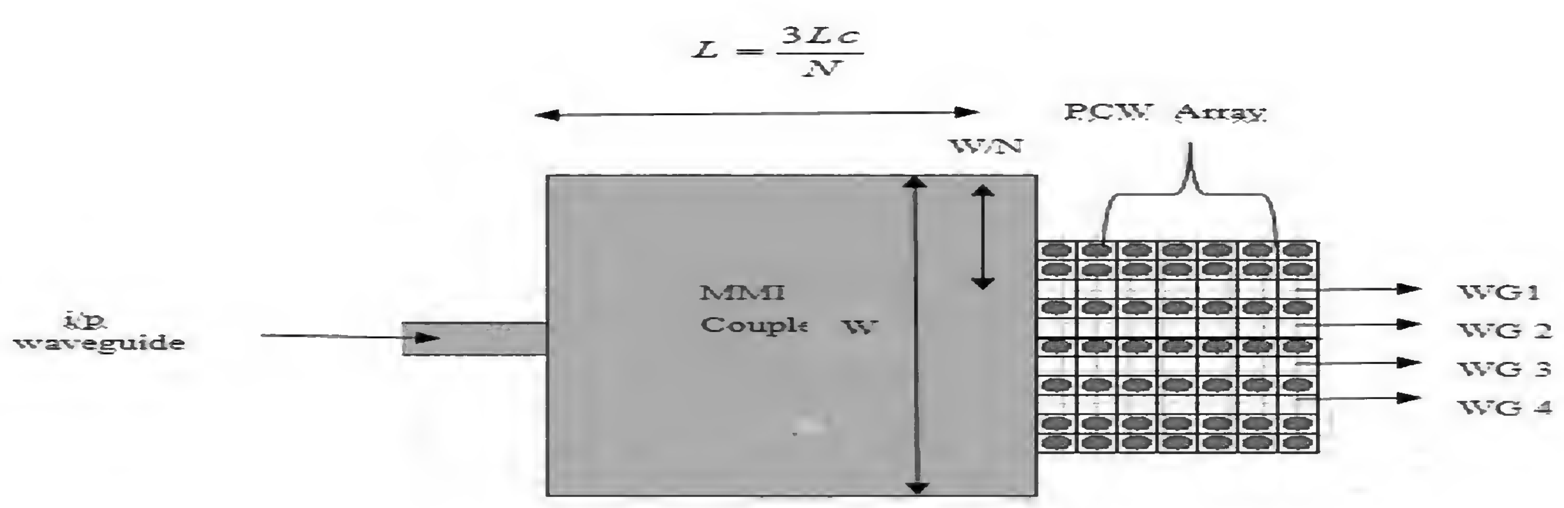


Figure 4: Schematic View of PCW Based 1x4 Power Splitter

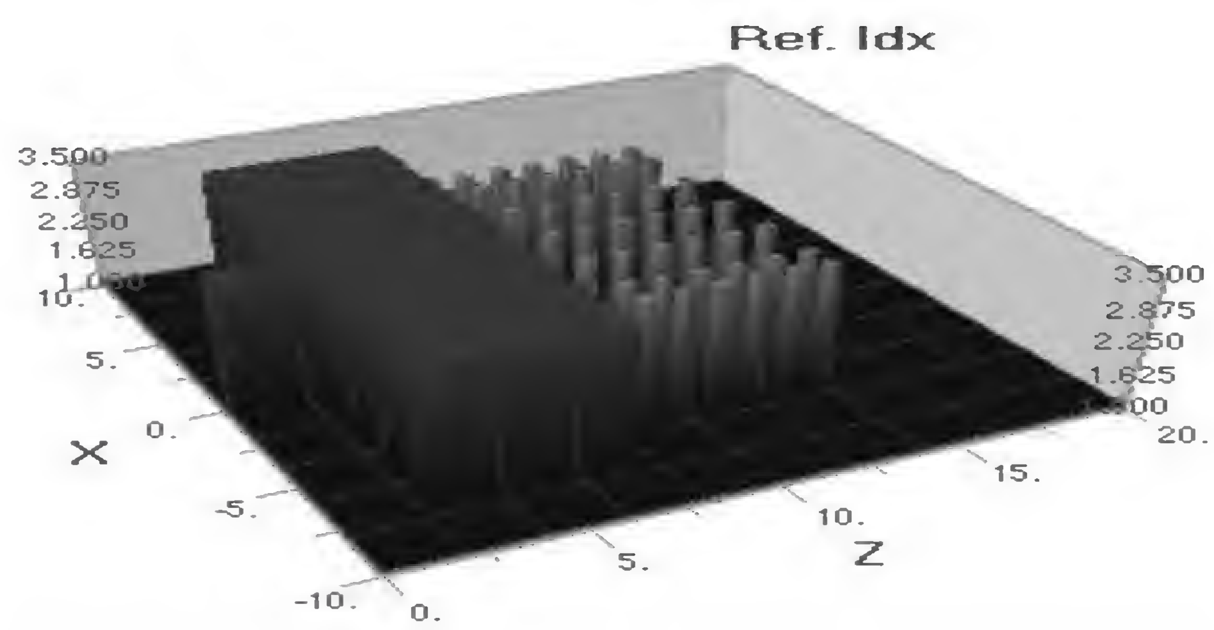


Figure 5: Refractive Index Profile of the 1x4 Power Splitter (PC with Rods in Air)

2. 2 Design of 1x4 Power Splitter on PC with Air Holes in Dielectric Background

The schematic diagram of the 1x4 Power Splitter based on PC with air holes in dielectric background is analogous to the Power splitter shown in Figure 4. The PC used here is a square lattice of air holes with radius 0.1a. MMI coupler is a

slab waveguide with refractive index n=3.45.The dimension of the MMI coupler is 3x5µm.MMI coupler is integrated with PCW array. The thickness of the guiding layer is 150nm.Substrate thickness is 690nm.These o/p PC waveguides are replacing the conventional waveguides. The four Photonic Crystal (PC) waveguides are created by eliminating four rows of air holes. (Creating line defect in PC) and the diameter of the air holes adjacent to the waveguides are varied as a/λ, a/2λ and a/3λ where λ is the operating wavelength(creating point defect in PC).The refractive index profile of this novel device is shown in Figure 6.

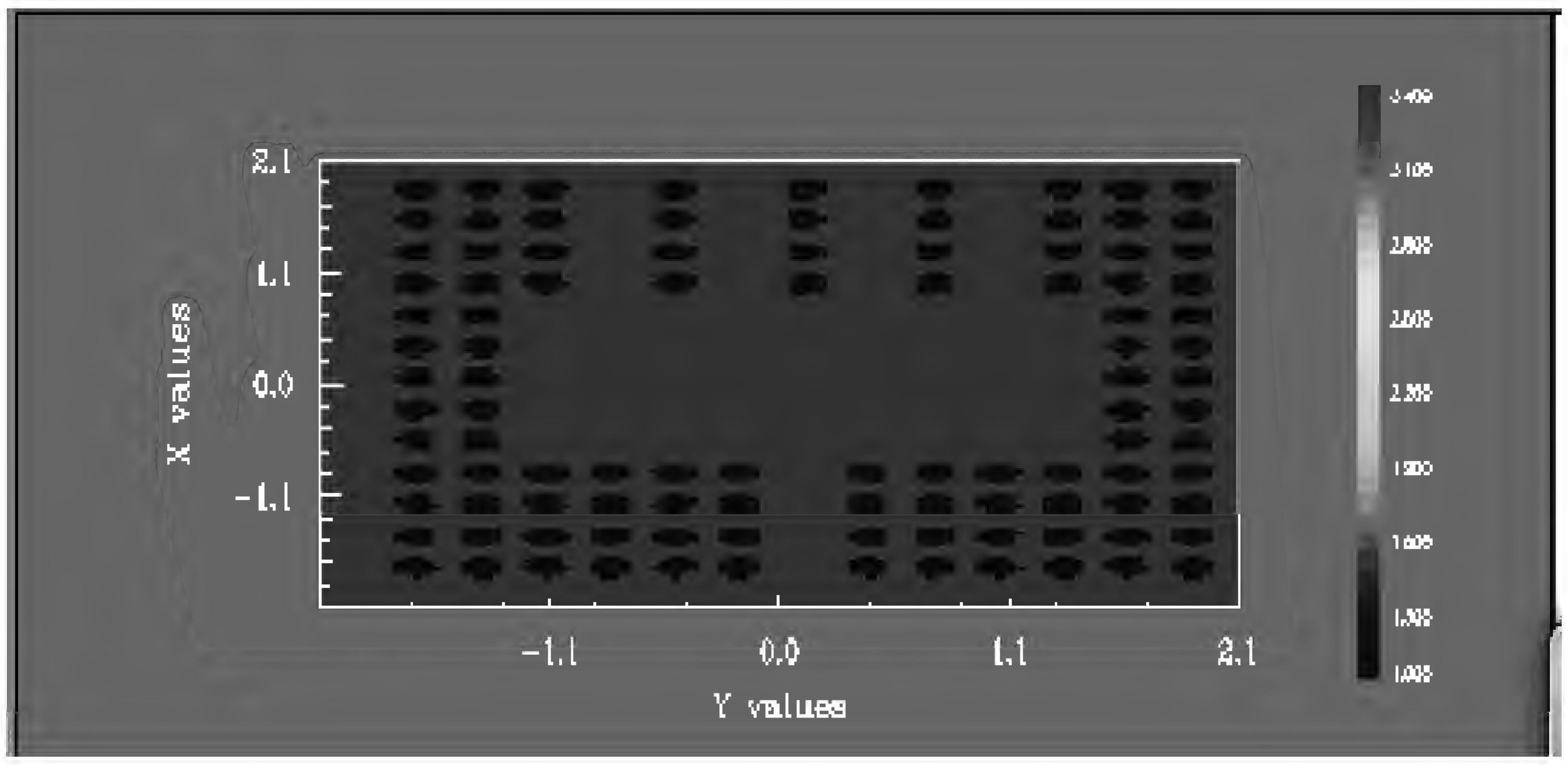


Figure 6: Refractive Index Profile of the 1x4 Power Splitter (PC with Airholes in Dielectric Background)

2.3 Analysis

The MMI coupler used in this novel Power splitter has one i/p waveguide, which is planar and the o/p is a PCW array comprising of four waveguides created by removing four rows of rods/air holes, to accomplish equal distribution. Whereas the variable Power splitter comprises of four rows of rods/air holes with unequal diameter. The geometry of the 1x4 variable power splitter with one input and four o/p waveguides is depicted in Figure 7. Allowed i/p and o/p locations are at the integer multiples of W/N of the total MMI width. Where "W" is the equivalent MMI width, which is the geometric width of the MMI coupler including the penetration into the neighboring material of the waveguide.

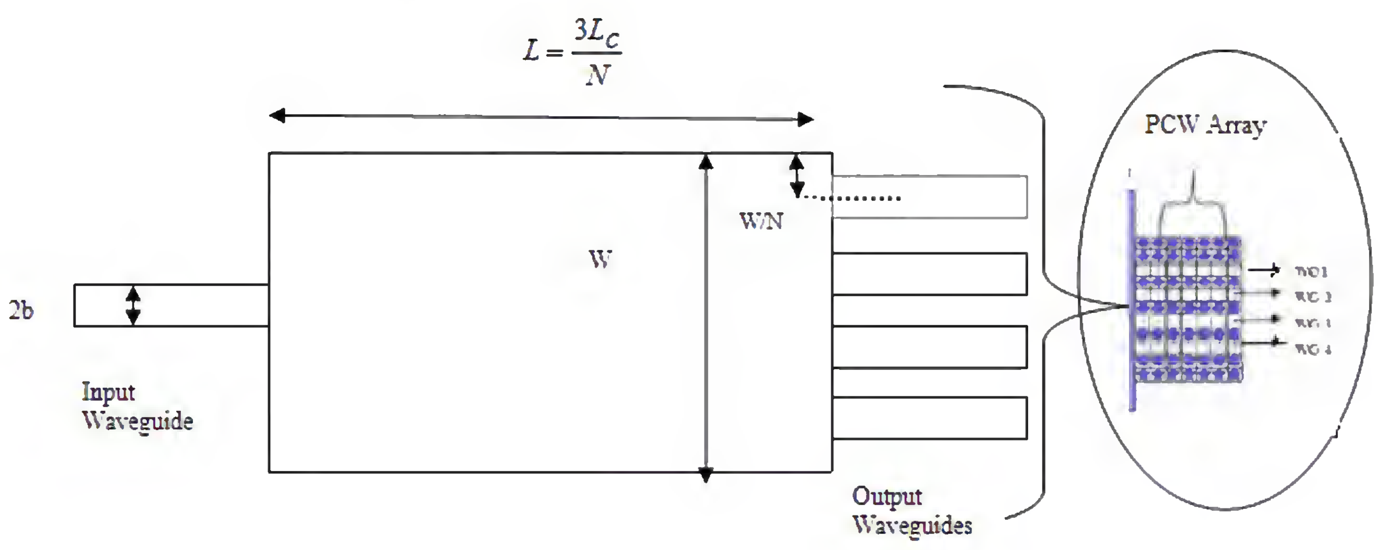


Figure 7: MMI Coupler, Where the o/p Waveguides are Replaced by PCW Array

The length of such a MMI coupler and the coupling length is given by the "Equation 1" & "Equation 2"

$$L_{\frac{M}{N}} = \frac{M}{N}.L_c \tag{1}$$

with

$$L_c = \frac{4 n_{eff} W^2}{3\lambda} \tag{2}$$

Where "M" is the possible MMsI lengths of overlap in MMI ,with (N-1) possible i/p and o/p waveguides. "n_{eff}" is the effective refractive index,λ is the operating wavelength and L_c is the coupling length of the MMI coupler. In our design the width of the PCW array =12a. The position of the o/p waveguides must be at "W/N".The width of the PCW waveguides are greater than or equal to 2a depending on the diameter of the dielectric rods/airholes adjecent to the waveguide. The width of the i/p waveguide is "b" µm.Length of of the coupler=(3Lc)/N.

The splitting ratio P_c/P_b depends on the width of the PCW waveguide and the effective index of the individual waveguide.Wherin P_c and P_b are the coupled power and the i/p power. To obtain the variable power splitting ratio, the normalized width of the o/p waveguides "dΩ" is varied by varying the size of the rods/airholes.This results in the variation of n_{eff} of each path.Hence L_c is varied resulting in flexible coupled power.The coupled power is given by the "Equation 3".

$$P_c \approx Cos^2(0.5.\pi.d\Omega) \tag{3}$$

The propagation constant β in the array section of Figure 7 of the power splitter depends on "dΩ" the normalized width variation.The propagation of light in the array section is computed using coupled mode theory[16]. The dipsersion offered by the array section contributes for phase shift in the array sections. The phaseshift varies with wavelength.However the phase shift is not important in this case.However the focus is on the coupled power.

The "dΩ" of the array waveguide in "Equation 4" is chosen such that maximum power is coupled to the individual waveguides at the central wavelength (1550nm).

$$d\Omega = \frac{m.\lambda_c}{n_{eff}}$$
$$m = order\ of\ the\ array$$
$$\lambda_c = Central\ wavelength$$
$$n_{eff} = Effective\ index \tag{4}$$

The power launched into the central waveguide is coupled to the neighboring waveguide in normal cases. The amount of power coupled to the adjacent waveguides depends on the coupling coefficient k. If there are n waveguides, light propagation in the n^{th} waveguide obeys the following first order coupled- mode equation given by the "Equation 5", "Equation 6" and "Equation 7" (Kogelink & Shank, 1972).

$$i\frac{d}{dz}a_n(z)+\beta_n a_n(z)+k_n[a_{n-1}(z)+a_{n+1}(z)]=0$$
$$2\leq n\leq N-1 \tag{5}$$

$$i\frac{d}{dz}a_n(z)+\beta_1 a_1(z)+k_1 a_2(z)=0;\ n=1 \tag{6}$$

$$i\frac{d}{dz}a_N(z)+\beta_N a_N(z)+k_N a_{N-1}(z)=0\ n=N \tag{7}$$

The coupling coefficient k and the propagation constant β is not same in the case of PCW array of the novel power splitter. If all the waveguides are identical then propagation constant is taken to be same (β1=β2=β3---=β) and (k_1=$\mathbf{k_2}$=k_3---=k). If one of the waveguides is excited initially ($a_{n=n0}(0)=a_0$). Then the solution of the above equations is given by "Equation 8".

$$a_n(z) = a_0(i)^{|n-n_c|}\exp(i\beta z)J_{|n-n_c|}(2kz) \quad (8)$$

Where "$a_n(z)$ is the amplitude of the guided modes in the parallel waveguides, obtained by solving the coupled mode equations. In the proposed device, all the three waveguides are excited as the o/p from the MMI coupler enters the four waveguides simultaneously. The value of the coupling length (L/a) required =30a >> length of the PCW waveguides. Therefore all the four waveguides behave as independent waveguides without any mutual coupling. Hence the amplitude of the modes is given by the "Equation 9"

$$a_n(z) = (a_0)\exp(-i\beta_n z) \quad (9)$$

Where (n=1,2,3,4) and the power entering each waveguide depends on "dΩ".

2.4 Losses

There is no bending losses and coupling losses as in the case of Photonic crystal "Y" splitter and Power Splitter based on Direction coupler principle. However there may be some losses while fabricating the device. This is due to the integration of the MMI coupler with Photonic crystal array. Furthermore, propagation losses can be ignored as the device is compact.

2.5 Applications

The novel device is multifunctional. It has several applications such as 1) True Time Delay Line (TTD) for antenna beam steering.2) Laser 3)Optical Cross Connect(OCC) 4) Mux/Demux 5) Biomedical Sensor 6)Gas Sensors. The device can be tailored for a particular applications by varying the no of i/p and o/p waveguides, using MMI region as an interaction region for sensing gas and adding a additional layer of analyte(DNA) on the GaAs layer.

3. RESULTS

Using hybrid polarization, we ascertained that PC lattice used for our investigation has a complete Photonic Band Gap(PBG) at the operating wavelength as shown in Figure 8. This is required to ensure that the device is polarization insensitive. The fundamental mode in PC with dielectric rods in air is TM polarized and that of PC with air holes in dielectric background is TE polarized. Former is calculated using full vectorial method and the latter by the semi vectorial method. This is shown in Figure 9a and Figure 9b. Propagation of light is tightly bound incase of PC with dielectric rods in air. However the fabrication process is complex as compared to the PC with air holes in dielectric background.

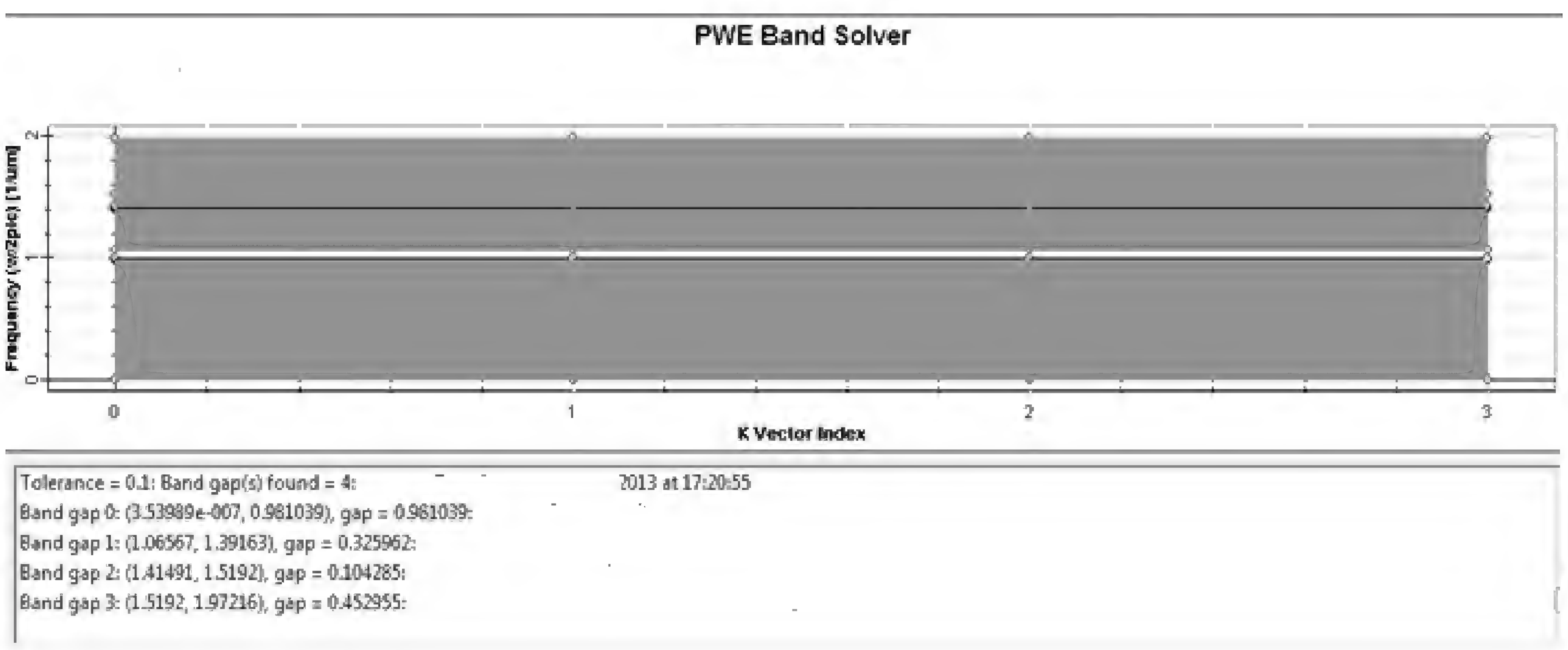
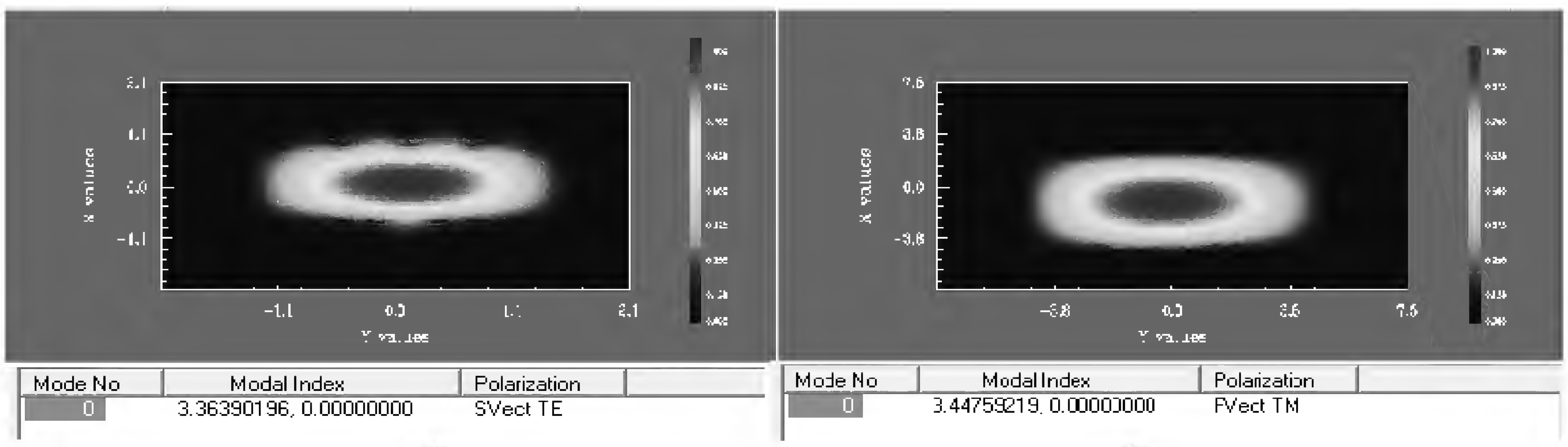


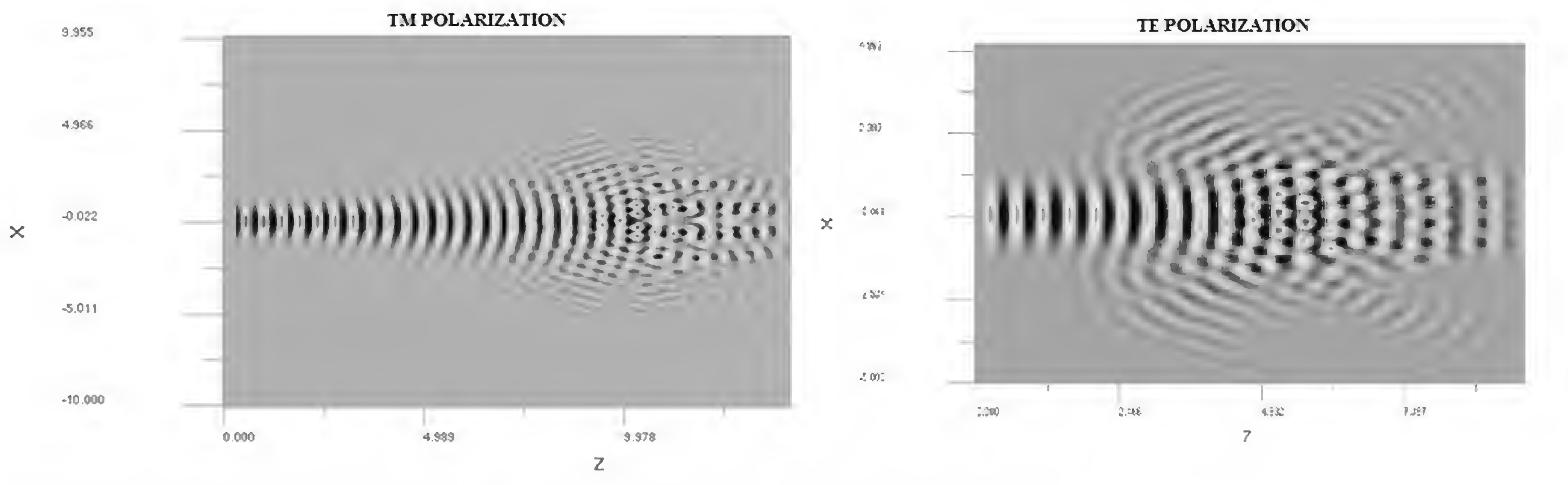
Figure 8: PBG Structure for PC for Hybrid Polarization



(a) (b)

Figure 9: Fundamental Mode in a) PC with Airholes in Dielectric Background b) PC with Dielectric Rods in Air

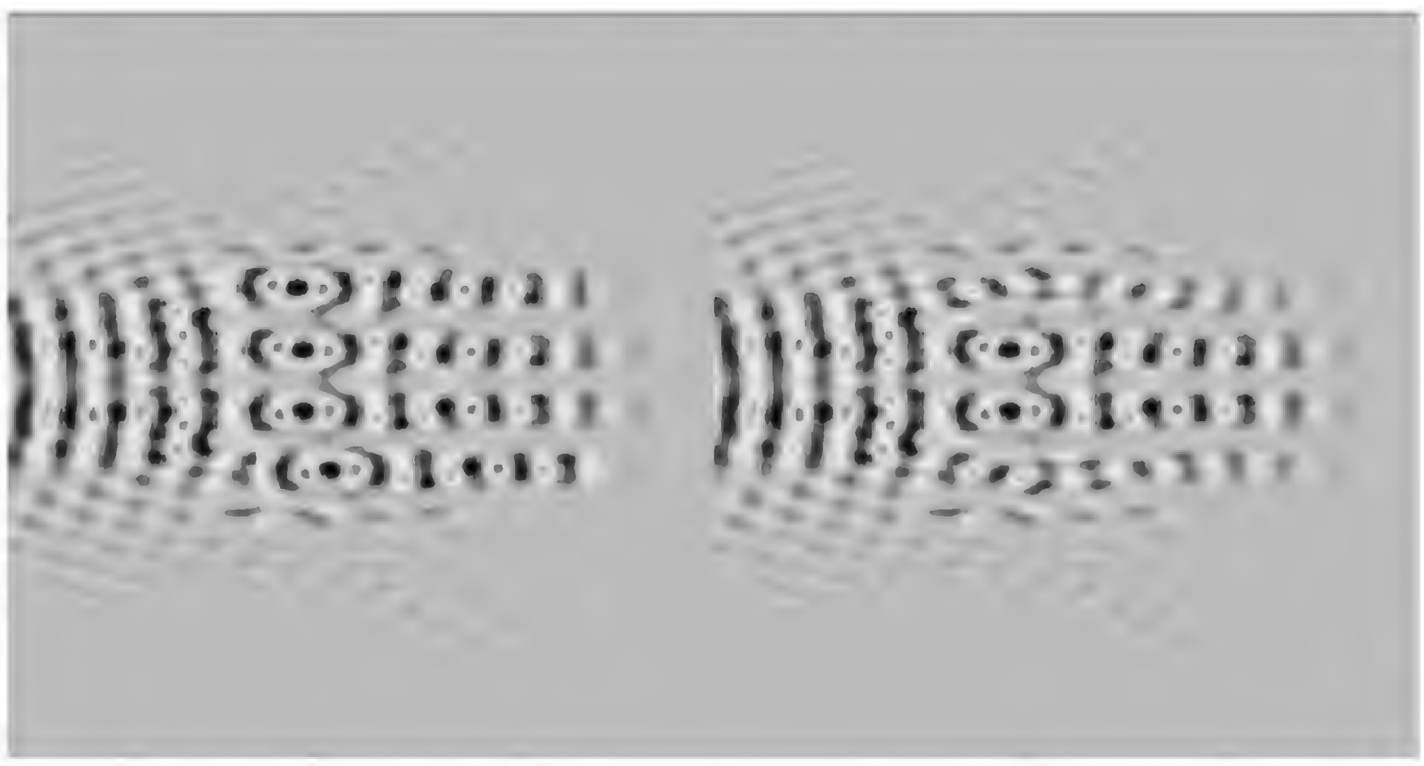
We performed the FDTD analysis (Yee, 1966) on PCW based 1x4 Power Splitter and observed the light propagation in both the cases. When continuous wave is launched through single mode i/p waveguide, it diverges in the MMI section, and enters the four o/p photonic crystal waveguides. This is shown in Figure 10a and Figure 10b.



(a) (b)

Figure 10: Light Propagation in 1x4 Power Splitter a) PC with Dielectric Rods in Air b) PC with Airholes in Dielectric Background

Incase of fixed Power Splitter, field associated with each o/p waveguide is equal. Where in the field associated with o/p waveguides varies in case of Variable Power Splitter. The propagation of light in the four o/p waveguides in fixed and variable Power Splitters are depicted in Figure 11.



(a) (b)

Figure 11: Light Propagation in a) Fixed Power Splitter b) Flexible Power Splitter

In Figure 11 we observe that, o/p beams are parallel incase of fixed 1x4 Power Splitter, where in the beams are bent, incase of variable Power Splitter. This is due to the variation in propagation constant “β” along each optical path, as we have varied the diameter of the dielectric rods/air holes in this case. Although there is some phase change, it does not

effect the performance of the Power Splitter. However this property can be exploited for designing the Mux / Demux and TTD.

We performed the numerical simulation to check whether the power splitting takes occurs as per theoretical analysis. This was ascertained by observing the poynting vector in both the cases as shown in Figure 12a and Figure 12b"Thus validating the function as 1x4 power splitter.

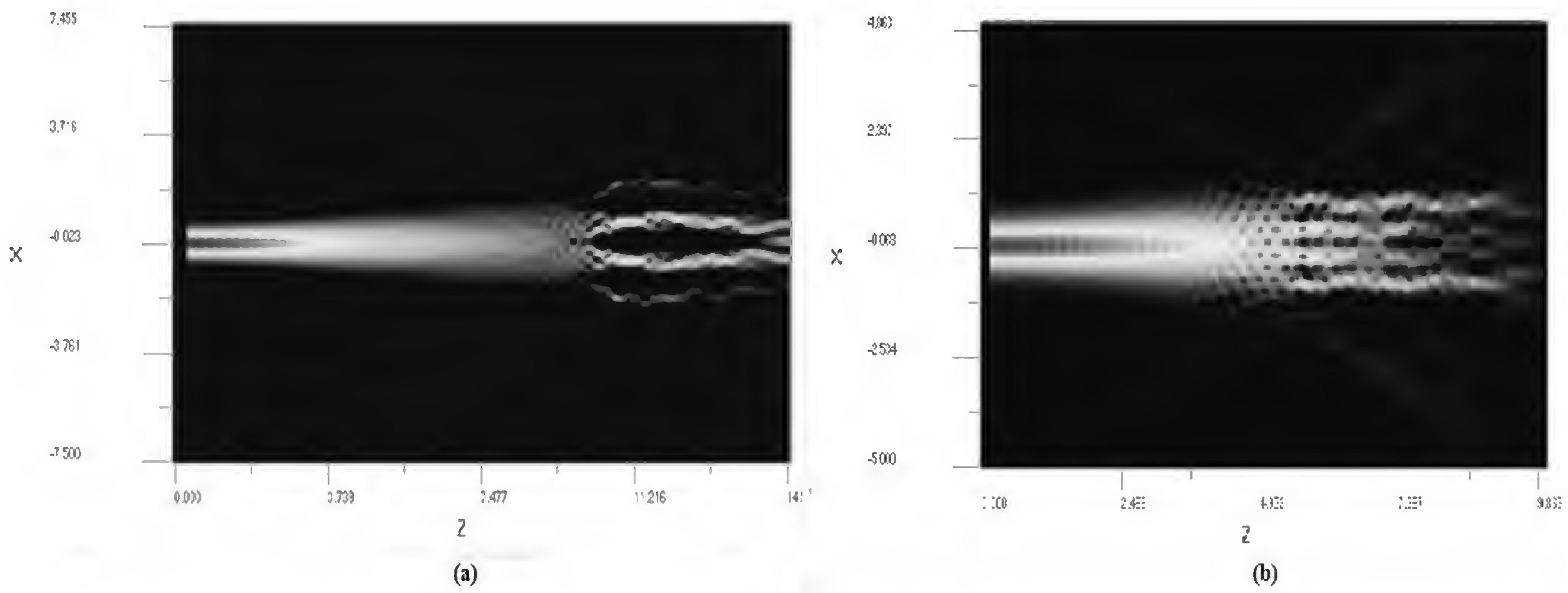


Figure 12: Poynting Vector Showing Power Distribution in Variable 1x4 Power Splitter a) PC with Dielectric Rods in Air b) PC with Air Holes in Dielectric Background

The variable power splitting ratio is obtained in both the cases due to the variation of n_{eff} with diameter of the rods/air holes as shown in "Figure 13a".Change in n_{eff} results in variable "dΩ" resulting in variable power distribution. Variation of n_{eff} with wavelength, an important phenomenon in PC which in turn results in a large value of dispersion. Variation of n_{eff} with λ and the dispersion graphs are shown in "Figure 13b" and "Figure 13c". Although it is a secondary parameter for the Power Splitter, these properties are the keys for the multi function behaviour of the proposed device.

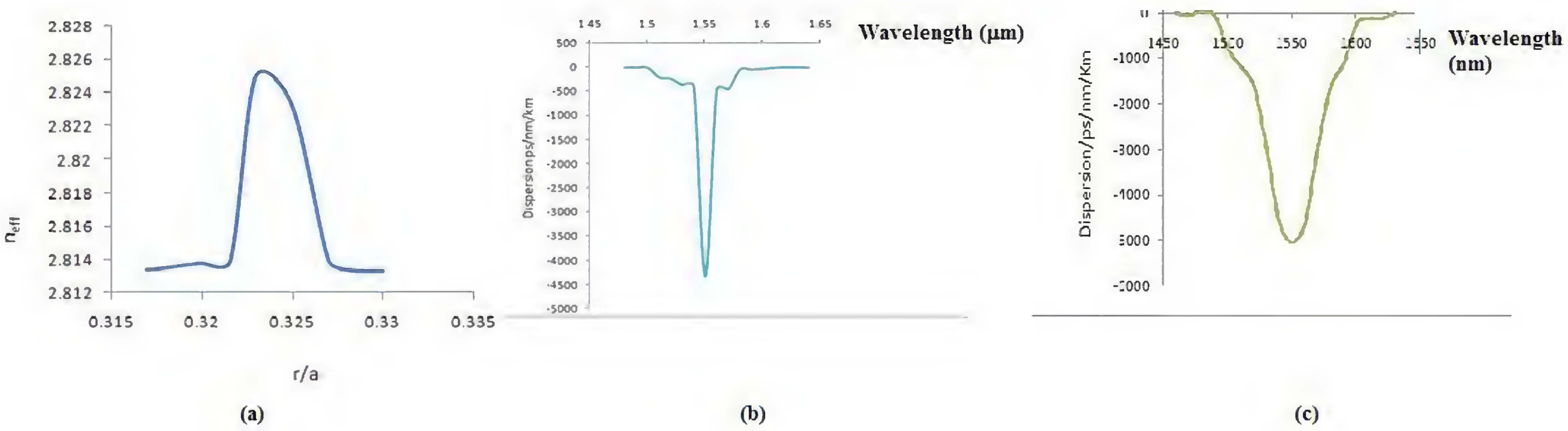


Figure 13: a) Variation of Neff with λ b) Dispersion in PC with Dielectric Rods in Air c) PC with Airholes in Dielectric Background

"Table 1" shows the comparison between two types of 1x4 Power Splitters discussed in our work.

Table 1: Performance of 1x4 Variable Power Splitters

Type	Dispersion ps/nm/Km	Device Length(µm)	Material	Coupling Ratio
PC (Dielectric rods in air)	-4500	14	GaAS	21-23% to each port
PC (Airholes in dielectric)	-5046	8	GaAS	19-21% to each port

4. DISCUSSIONS

Here we propose a novel design of the 1x4 PC based variable Power splitter considering square lattice of air holes/rods. This work can be carried on other lattice structures such as triangular lattice of air holes/rods. The performance of each structure is characterized and compared with each other for maximum power transmission. By engineering the various parameters of Photonic Crystal and MMI coupler we can also design 1x2, 1x3 and 1x8 Power Splitters. We test the power splitting bandwidth by injecting an optical wave deviated from the central wavelength. The available bandwidth around the central frequency is 2%.However by optimizing the design parameters of the MMI coupler and PC we can increase this value of bandwidth such that it is sufficient enough to cover the bandwidth of the laser diodes used in optical communication network.

5. CONCLUSIONS

The performance analysis of two types of power splitters shows that PC-Power Splitter with rods in air has higher coupling coefficient and high efficiency. The power coupling characteristics of these novel devices are demonstrated using FDTD method.The coupled mode equations are derived to compare the power transfer in each waveguides.Numerical simulation results show that power can be divided efficiently in a compact devices which spans 14-15μm.By varying the d/a of rods and air holes we can obtain the flexible power splitting ratio.

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